RISING SEAS AND STRONGER STORMS – DELAWARE'S ADAPTATION IN THE FACE OF UNCERTAINTY DRAFT 9 February 5, 2011

Sea level rise (SLR) and the stronger storms expected as the earth continues to warm are likely to be among the most damaging consequences of global climate change for Delaware, which has a long coastline for a small state, as well as the lowest average elevation of any state in the country (20 m or about 60 ft).[i] In this paper I will focus on the science behind SLR, including Earth's past behavior, and discuss possible - but very uncertain – future sea level trajectories - both how high sea level could go and how long it might take to get there. Some idea of how fast and how far sea level may go is important for future planning by state and local governments and by those who own property along the coast. Another important issue, which I will not address, is how high above mean high tide the water may go as a result of stronger storms.

The questions I will address are the following:

- Why is sea level rising?
- Why is the global average temperature (T) rising?
- What is radiative forcing, and how does it depend on CO_2 and other greenhouse gases?
- How is the concentration of CO_2 changing with time?
- How does T depend on CO_2 concentration?
- How does SLR *at equilibrium* depend on T?
- How fast will the sea rise?
- How should we plan in the face of uncertainty?

Why is sea level rising?

Sea level along the Delaware coast is rising as a result of three factors: 1) subsiding (sinking) land, 2) thermal expansion of sea water as its temperature rises, and 3) an increase in the amount of water in the oceans as glaciers on land melt or slide into the sea. During the past century sea level at Lewes (relative to the land) rose about a foot – about half due to subsidence and the rest to expanding water and loss of ice on land.[ii] Thermal expansion and ice melting both require heat;[iii] most of which comes from the sun.

Why is the global average temperature (T) rising?

One of the key scientific concepts behind SLR is the Law of Conservation of Energy, which states: **In ordinary (non-nuclear) physical, chemical and biological processes energy is neither created nor destroyed - only converted from one form to another.** This means that the energy coming into Earth's oceans, land and atmosphere in the form of absorbed solar radiation must be balanced by radiation going back into space for the global average temperature to remain constant. An imbalance can be caused by: 1) a change in the intensity of the sun's radiation, 2) a change in the fraction of incoming radiation that is reflected without being absorbed (the 'albedo'), and 3) the concentrations of greenhouse gases (GHGs) in Earth's atmosphere – particularly water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and fluorochemicals.

Figure 1 shows the global annual average temperature at Earth's surface over the last 130 years. During that time the average temperature has increased about 0.8°C (about 1.5°F), with most of the increase in the last 30 years.[iv] The error bars show the estimated uncertainties in the measurements. The last decade has been the warmest on record.[v] 2010 tied 2005 for the highest annual average.[vi]

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 1. Global average temperature since 1880.

What is radiative forcing, and how does it depend on CO_2 and other green house gases?

Any body with a temperature above absolute zero (-273°C) will radiate electromagnetic radiation over a range of wavelengths, with maximum emission at a wavelength that decreases as the temperature increases. Figure 2 shows the approximate distributions of solar radiation absorbed from the sun and emitted into space from the earth. (Note the nonlinear wavelength scale.) The sun, with a surface temperature of about 10,000°F, has its emission maximum (at 0.6 microns) in the visible part of the spectrum; the earth, with an average surface temperature of about 60°F, has its maximum (at 15 microns) at longer wavelength in the infrared (IR).

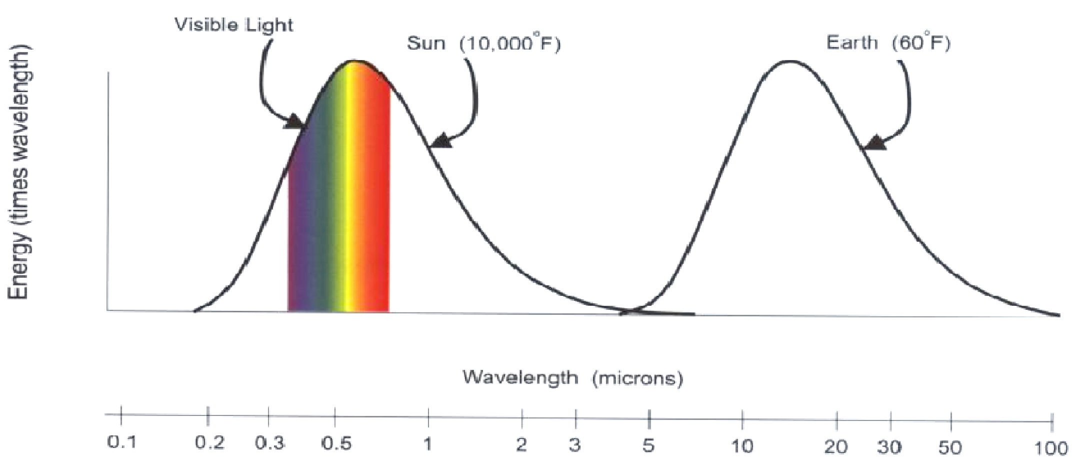


Figure 2. Radiation absorbed from the sun and emitted by the earth. The wavelength scale is nonlinear. Temperatures given are the approximate surface temperatures (°F).

Radiation balance requires that the average intensity of radiation absorbed from the sun (about 250 watts per square meter (W/m^2)) equals the average intensity of radiation emitted. The increasing temperature shown in Figure 1 indicates that more radiation is now being absorbed than is going out. Though there have been contributions from increasing solar radiation and reduced albedo since the beginning of the Industrial Revolution in about 1750, scientists have concluded that the radiation imbalance is due mostly to increasing concentrations of greenhouse gases.[vii] The contributions to the imbalance, called "radiative forcings", are shown in Figure 3. The net anthropogenic (human caused) component of about 1.6 W/m^2 is the net effect of human activities since 1750 on the radiation balance. That doesn't sound like much, but the earth has a large area, and a lot of heat can be absorbed over time.[viii]

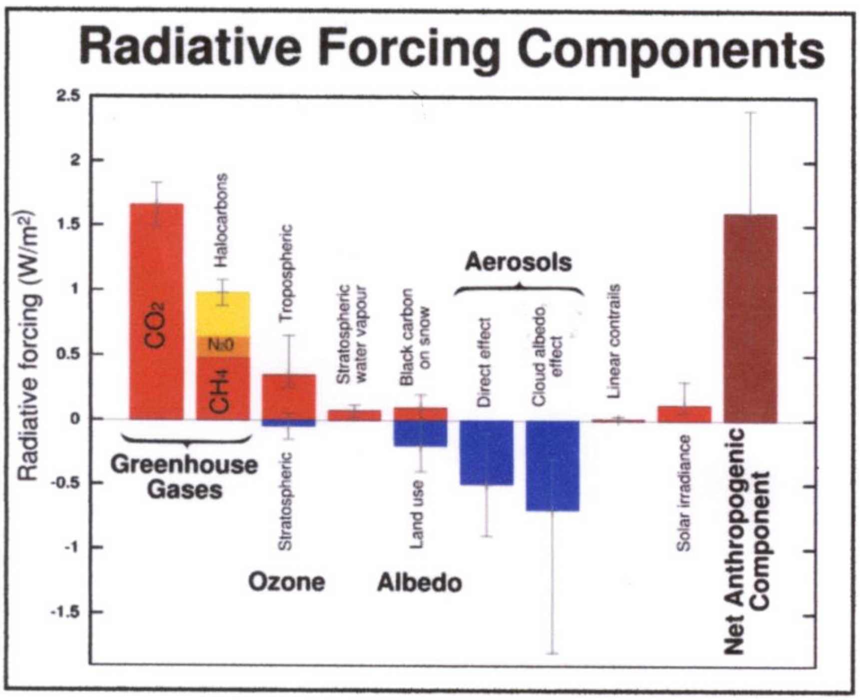
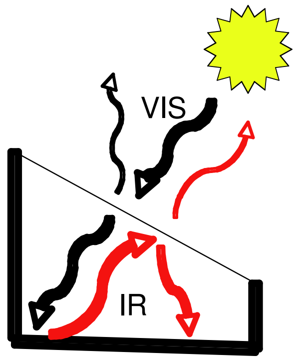


Figure 3. Contributions to radiative forcing from changes in greenhouse gases, aerosols, and solar irradiance.[ix] Uncertainties are indicated by error bars.

The way greenhouse gases (GHGs) affect the radiation balance is shown by the schematic greenhouse in Figure 4. The thin sloping line represents the glass roof and the heavier lines the walls and floor. Visible radiation is indicated by wavy black arrows and infrared by red; the arrow thickness indicates radiation intensity.

The Greenhouse Effect



Earth's GHGs: H_2O, CO_2, CH_4, N_2O, O_3, Halocarbons

Figure 4. The Greenhouse Effect

The solar radiation coming from the sun, mostly in the visible part of the spectrum, passes through the glass on the roof of a greenhouse and warms the plants and floor, which then radiate in the IR. Glass is not transparent to IR, so it is absorbed and heats the glass. The warmer glass radiates some energy up and out but also back down, making the inside of the greenhouse warmer that it would otherwise be. Your car, parked in the sun with the windows rolled up, acts the same way. Earth doesn't have a glass roof, but it has GHGs in the atmosphere that act similarly – allowing solar radiation to pass in but impeding IR radiation from going back out. The greenhouse effect is a good thing; without it Earth's average surface temperature would be about 0°F (-18°C), and life as we know it would not be possible; with it, the average temperature is nearly 60°F (15°C), but it's increasing as the concentrations of GHGs increase.

How is the concentration of CO_2 changing with time?

We have accurate instrumental measurements of CO_2 concentration, made on the top of Mauna Loa (a high mountain on Hawaii's South Island), for about 50 years. Earlier atmospheric CO_2 concentrations can be determined from air bubbles trapped in ice cores taken from glaciers. Results for the last 1000 years or so are shown in Figure 5.

Atmospheric CO_2 Concentration

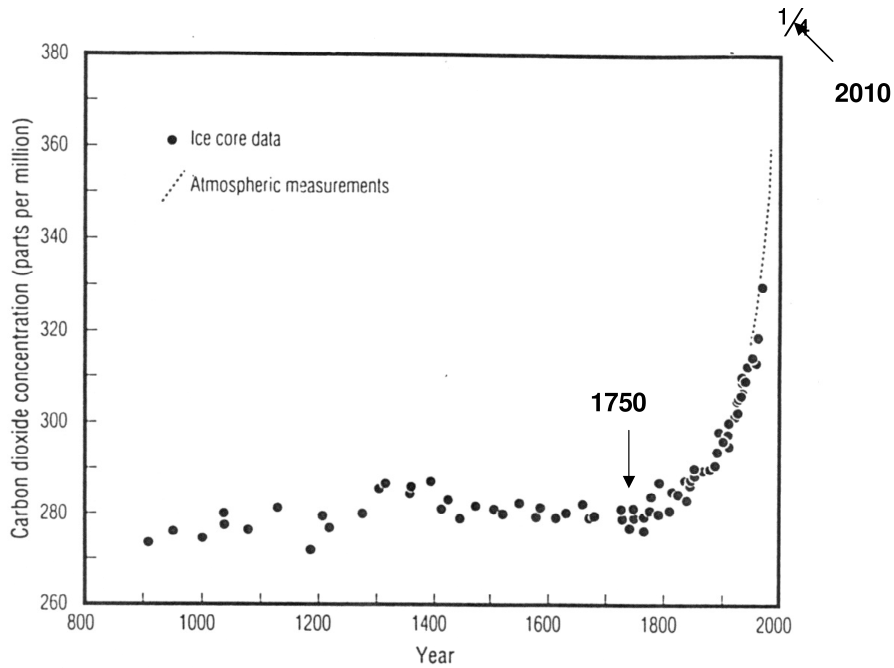


Figure 5. Atmospheric CO_2 concentrations determined from ice core (solid points) and instrumental measurements (dashed line and open point for 2010)

The concentration of CO_2 was about 280 ppm (parts per million)[x] in 1750, at the beginning of the Industrial Revolution, and is about 390 ppm in 2011, and rising by about 2 ppm per year. The rate is expected to increase as emissions increase. The concentration will double from its preindustrial value (to 560 ppm) well within this century at the rate things are going.

How does T depend on CO_2 concentrations?

The dependence of global average temperature on the concentrations of CO_2 and other GHGs can be estimated based on models of the atmosphere, land, ocean, ice system, and by looking at Earth's climate history. The dependence is nonlinear, as can be seen in Figure 6. The thin vertical lines mark concentrations of 280 ppm (the value in 1750), 560 ppm (doubled) and 1120 ppm (doubled again). The thicker vertical line at 390 ppm shows where we are in 2011. The horizontal red line at 2°C is marked 'Danger' because many feel that dangerous climate change can be avoided only if the global average warming does not rise above that line.[xi] The horizontal red line at 4°C is marked 'No Ice' because no glacial ice is expected at equilibrium, even in Antarctica, if the global average warming remains at or above that line.

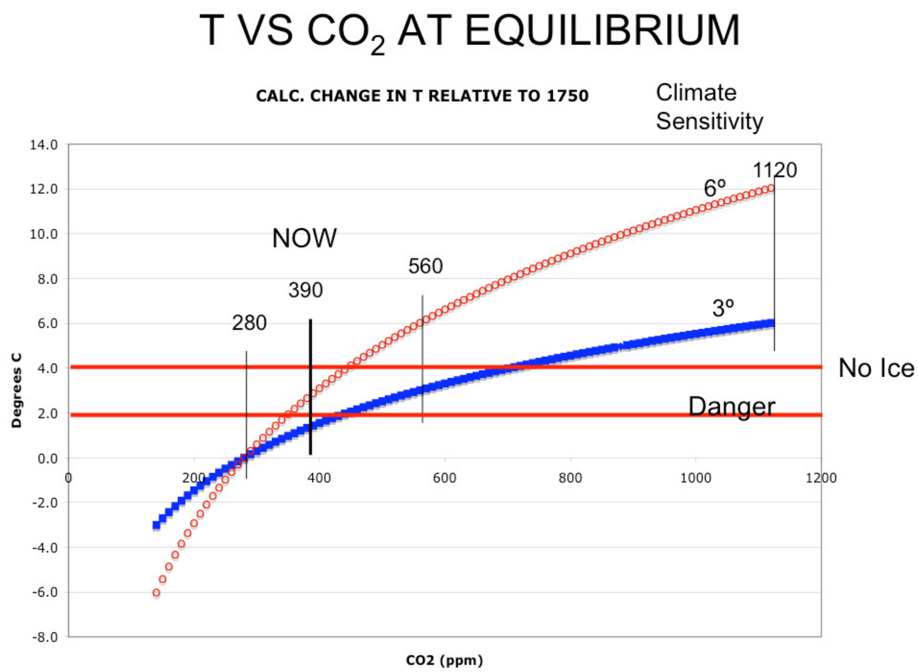


Figure 6. The global average temperature change calculated at equilibrium for increasing concentrations of CO_2 and climate sensitivities of 3° (lower curve) and 6°C (upper curve) for CO_2 doubling.[xii]

"Climate sensitivity" is the temperature increase expected for each doubling of the CO_2 concentration, once equilibrium is reached for a fixed concentration of CO_2, and radiation balance is reestablished. The sensitivity of 3° is based on mathematical models and was considered to be the most probable value in the 2007 report of the Intergovernmental Panel on Climate Change (IPCC).[xiii] The sensitivity of 6°C is based on Earth's past climate history, and includes slow changes in albedo, as reported in an important paper in 2008 by Hansen and others.[xiv]

How does SLR at equilibrium depend on the global average temperature?

If we look at Earth's deep sea temperatures and glaciation history over the last 65 million years (My), shown in Figure 7, we see that the temperature reached a maximum about 50 My ago and then started a slow decline after the Indian tectonic plate ran into Asia and lifted the Himalayas. Bicarbonate minerals formed about that time indicate that the CO_2 concentration was above 1100 ppm. It gradually decreased as erosion of the mountains washed calcium silicate down into the oceans, where the calcium combined with CO_2 to form calcium carbonate (now limestone). Ice did not begin to form in Antarctica until about 35 My ago, when the concentration had fallen to about 450 ppm. Northern Hemisphere ice sheets didn't start to form until about 5 My ago. An 8-minute discussion of Figure 7 by James Hansen can be found on YouTube.[xv] The difference in timing between hemispheres is probably due to differences in elevation and latitude. The South Pole is on a large landmass with mountains, while the North

Pole is surrounded by the Arctic Ocean and has a much lower average elevation. Permanent ice forms on mountaintops before it forms near sea level.

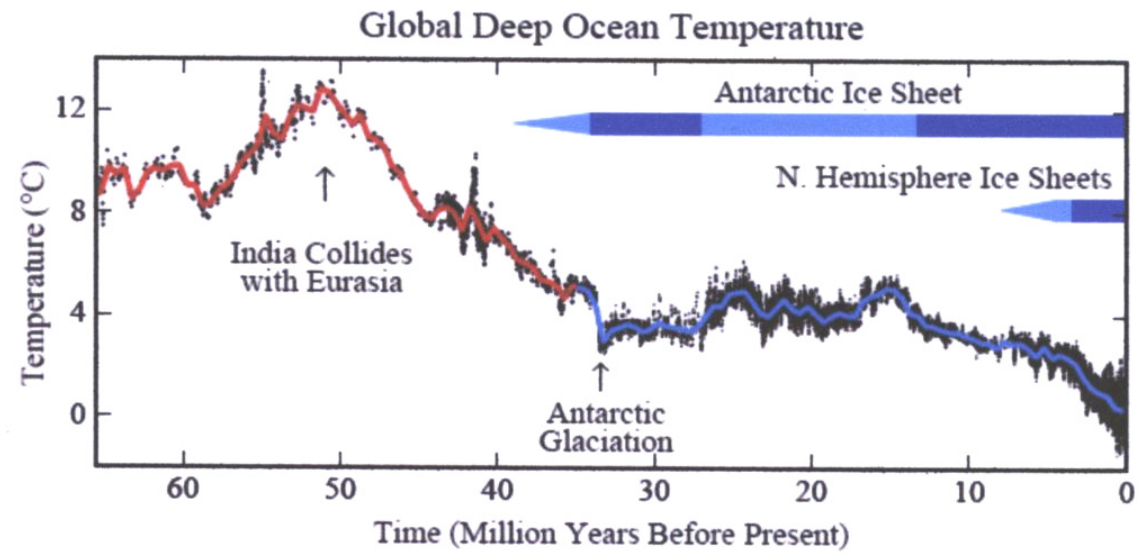


Figure 7. Deep-sea temperatures and glaciation during the past 65 million years[xvi]

How does SLR at equilibrium depend on global average temperature (T)?

Figure 8 shows the dependence of sea level on T from the coldest time of the last ice age 20,000 years ago when sea level was 120 m lower than now, and temperature was 6°C colder, to a time 40 million years ago when there were no glaciers, temperature was 4°C warmer, and sea level was 80 m higher. The slope of the line is 20 m per °C for the solid points (at equilibrium). The open point labeled 'Projection for 2100' is for a temperature 3°C warmer than today and a sea level rise of 1 m (not at equilibrium).

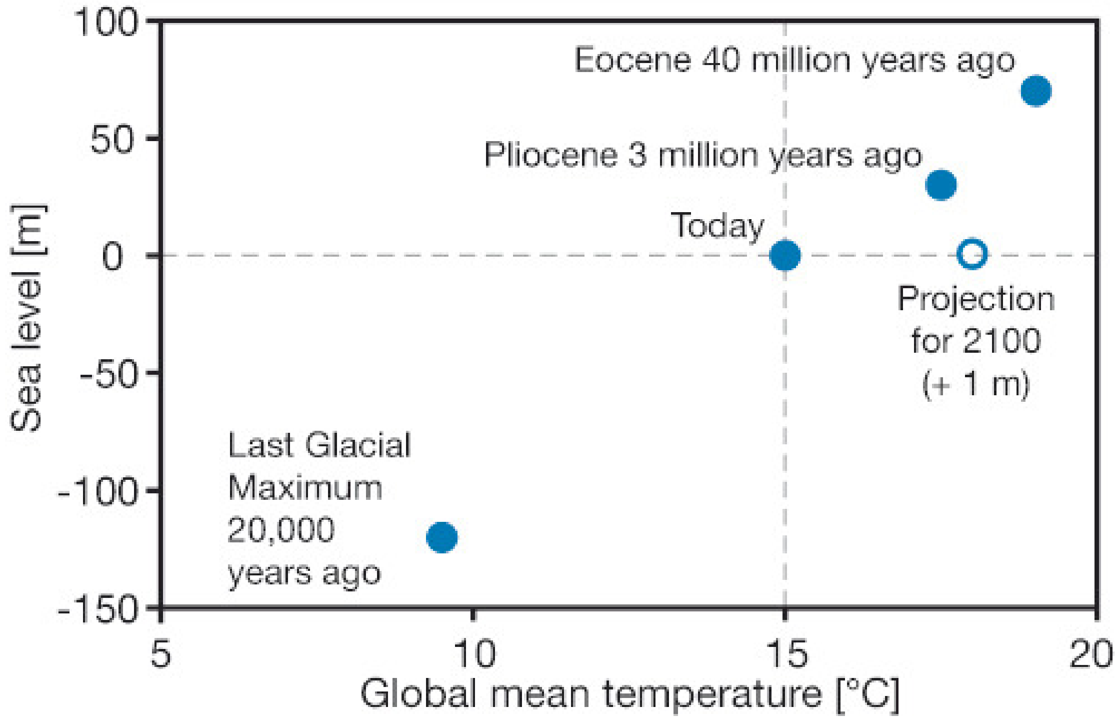


Figure 8. Sea level rise and global average surface temperature from the paleoclimate record (solid points) and a projection for 2100 (open point).[xvii]

The reason that the point projected for 2100 is so far from the line defined by the other points is that it takes a long time to heat the ocean and melt the ice enough to reach thermal equilibrium.

Figure 9 shows the effects of large rises in sea level on Delaware and nearby parts of MD and NJ.

Figure 9. Effects of large rises in sea level on DE and neighboring states.[xviii]

The light green areas are above sea level for a 15 m rise, corresponding to complete loss of ice on Greenland and West Antarctica. The dark green area is what is left if the big ice in East Antarctica is also lost, raising sea level by 80 m.

How fast will the sea rise?

Figure 10 shows how the sea level rose with time coming out of the last ice age, from over 20,000 years ago to the present, based on the analysis of coral at various sites. You can see the sea level rose slowly at first, then increased in speed, reaching a maximum about 14,000 years ago during an event labeled Meltwater Pulse 1A, when it appears to have risen by 10-20 m in a few centuries.[xix] Steven Earle has suggested that the rapid SLR was mostly from the loss of ice in Antarctica.[xx]

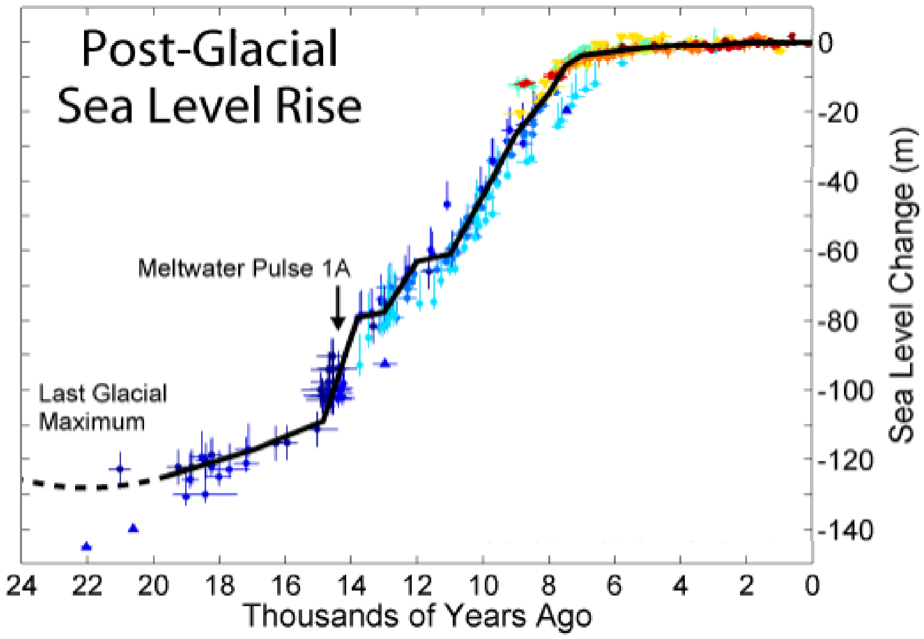


Figure 10. Sea level rise since the last ice age.[xxi]

Stefan Rahmstorf has been a proponent of what he calls semi-empirical models of SLR, in which the rate of melting is proportional to the warming. Using this approach, and fitting his model to the recent rate, he projects that the sea level in 2100 will be 124 cm (1.24 m) above what it is now.[xxii] He shows a graph of a range of estimates based on various authors using similar models, with most in the range of about 0.5 to 2.2 m. He says that the rate of SLR tripled during the 20th Century, consistent with an accelerating rate.

In recent years NASA has been able to measure the loss of ice on Greenland and Antarctica directly by satellites, using very accurate measurements of the distance between a pair of them in the same orbit, one trailing behind the other. As the lead satellite approaches a large ice mass (e.g., Greenland), the gravitational attraction of the ice pulls on it more strongly than on the more distant trailing satellite, increasing the distance between them. Conversely, once the first satellite has passed the ice, gravity slows the first and speeds the second, reducing the distance between them. Figure 11 shows what the pair of satellites might look like from space (though the actual distance between them would be hundreds of miles).

GRAVITY SATELLITE ICE MASS MEASUREMENTS

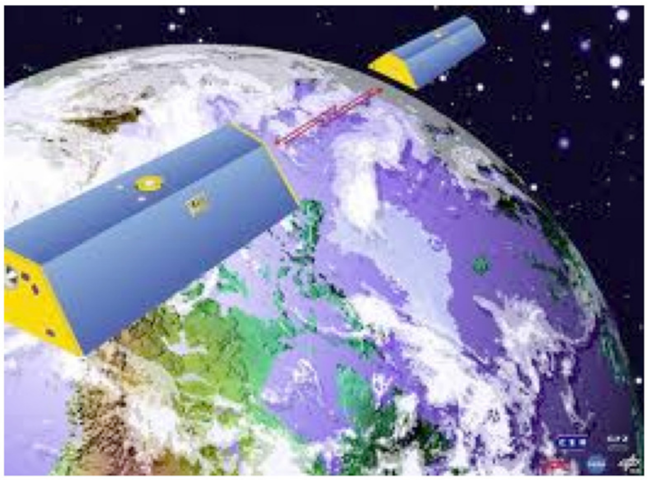


Figure 11. Gravity satellite ice mass satellites as seen from space.[xxiii]

Figure 12 shows the changes in ice mass of Greenland over a 6-year period from about 2003 to 2009. The vertical scale has units of 200 Gt; 200 Gt of ice will produce 200 cubic km (about 43 cubic miles) of water. The seasonal variation in the mass of Greenland ice is clear, with the minima in late fall. Most striking is the increasing slope of the curve with the annual variation removed. <u>The rate of Greenland ice loss doubled in a 6-year period</u>! Antarctica is also losing ice at an increasing rate, but the signal is noisy.

GREENLAND GRAVITY SATELLITE ICE MASS MEASUREMENTS

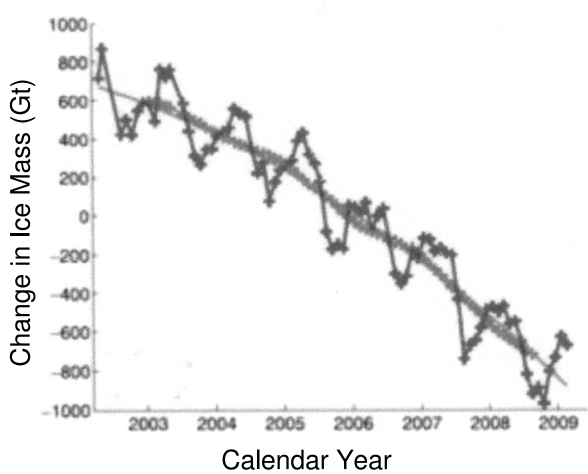


Figure 12. Gravity satellite measurements of the changes in ice mass in Greenland from 2003-2009.[xxiv]

We don't know if the 6-year doubling of the rate of ice loss from Greenland (corresponding to a 12.5% per year compounded rate) will continue, but if it does, all 2.6 million cubic km of ice will be gone in 60 years, raising sea levels by 7 m. The loss of Antarctic ice – mostly from West Antarctica - is also accelerating, but at a slower pace.[xxv]

We don't yet have good mathematical models to predict how fast ice on Greenland and Antarctica will return to the sea. Some of the major uncertainties are:

- Climate Sensitivity – how much global average temperature T will change for a doubling of CO_2 concentration
- The trajectory of future GHG emissions - including methane from hydrates that release methane when warmed
- How fast equilibrium T will be reached once the composition of the atmosphere is no longer changing
- The mechanisms of ice loss from Greenland and Antarctica
- When tipping points might be reached

Most model projections of future climate change consider only the direct emissions of CO_2 and other GHGs as a result of human activities; they don't consider the release of GHGs that could be released indirectly from reservoirs of carbon as the climate warms. One such GHG is methane – a gas that has a Global Warming Potential (GWP) 25 times that of CO_2.[xxvi] Such a release happened 55 million years ago, causing what is called the Paleocene-Eocene Thermal Maximum. A release of a large amount of methane (at least 2000 GtC; our present atmosphere contains about 800 GtC as CO_2) over a period of a few centuries caused global average temperatures to increase by about 5°C. The temperature excursion 55 My ago can be seen to the left of the broad peak in Figure 8. Oxidation of the methane to CO_2 by chemical reactions in the atmosphere and the absorbtion of the CO_2 into the oceans made them so acidic that calcium carbonate was not longer chemically stable, the base of the food chain was knocked out, and an oceanic extinction event occurred. You can read the details in a paper posted by the LWVUS titled, **Positive Feedbacks and Climate Runaway – The Need to Act without Delay**.[xxvii]

How should we plan in the face of uncertainty?

In cases like this, with unknown probabilities but very large consequences, environmentalists use the Precautionary Principle, which says, "Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."[xxviii] In the case of sea level rise in Delaware, I suggest that planning for major investments by state and local governments should include a consideration of the possibility that SLR by 2100 could be considerably more than 1.5 m – perhaps as much as 5 m or more. John Mercer, a scientist at the Ohio State Institute of Polar Studies, warned of this possibility over 30 years ago.[xxix] Government leaders should keep a very close eye on SLR in Delaware, loss of ice in Greenland and Antarctica, and on the behavior of precipitation and storm surges as the climate changes – modifying their adaptation plans and policies as required by the latest available science.

I feel strongly that adaptation to sea level rise should be part of a comprehensive Delaware energy/climate change plan that: 1) brings green industries and jobs to Delaware,

2) sets targets and a timetable for GHG emission reductions, and 3) educates policy makers and the public. Delaware should lead by example. A lot is at stake.

What about climate skeptics?

There is a small but outspoken group of scientists and others[xxx] who challenge the scientific consensus[xxxi] that: 1) The Earth is warming and its climate is changing; 2) The major cause is the addition of GHGs to Earth's atmosphere – especially CO_2 formed by burning fossil fuels; and 3) If we keep adding GHGs to the atmosphere there is an increasing risk of doing serious damage to the climate system. John Cook has a web site called SkepticalScience,[xxxii] where he summarizes the evidence for global warming in a single graphic and addresses the ten most used skeptic arguments, including: It's really the sun; Climate's changed before; There's no consensus; Antarctica is gaining ice; and others.

Submitted by Chad Tolman to the Delaware SLR Advisory Committee
For the League of Women Voters of Delaware

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[i] **List of U.S. states by elevation**. At:
http://simple.wikipedia.org/wiki/List_of_U.S._states_by_elevation

[ii] **Climate Change and Delaware**, EPA 230-F-97-008h. At:
http://www.awm.delaware.gov/Info/Regs/Documents/de_impct1.pdf

[iii] It takes 1 Cal (4.18 kJ) to raise the temperature of 1 kg of water 1°C and 80 Cal (334 kJ) to melt 1 kg of ice. See: **Enthalpy of fusion**. At: http://en.wikipedia.org/wiki/Enthalpy_of_fusion

[iv] http://www.ncdc.noaa.gov/oa/climate/research/anomalies/index.html

[v] **NOAA: Past Decade Warmest on Record According to Scientists in 48 Countries**. At:
http://www.noaanews.noaa.gov/stories2010/20100728_stateoftheclimate.html

[vi] ***Science News***, January 13, 2011. At:
http://www.sciencenews.org/view/generic/id/68761/title/2010_ties_record_for_warmest_year_yet

[vii] IPCC, **Climate Change 2007: The Physical Science Basis, Summary for Policy Makers**, at:
http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf

[viii] 1.6 watts is about the power used by five of those tiny Christmas tree lights.

[ix] Water vapor is a very important GHG but is not shown in Figure 3 because of its short lifetime (a few days) in the atmosphere. The total amount of water vapor in the atmosphere increases as the global average temperature increases, and its effect is taken into account in the climate sensitivity to CO_2 doubling.

[x] A CO_2 concentration of 390 ppm means that 390 molecules out of a million in air are CO_2.

[xi] **Avoiding Dangerous Climate Change**. At:
http://en.wikipedia.org/wiki/Avoiding_Dangerous_Climate_Change

See also: **When Global Temperature Rises by 2 Degrees Celsius**. At:
http://www.america.gov/st/energy-english/2010/January/20100106144306lcnirellep0.4811212.html#ixzz1B8OAaeK1

[xii] For a climate sensitivity of 3° for CO_2 doubling, T=10*log([CO_2]/280), where [CO_2] is the concentration in ppm and 280 ppm was its concentration in 1750; for 6°, T=20*log([CO_2]/280).

[xiii] IPCC, **Climate Change 2007: Synthesis Report, Summary for Policy Makers**. Figure SPM 11 on p. 21. At: http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf

[xiv] James Hansen et al., **Target CO_2: Where Should Humanity Aim?**
http://www.columbia.edu/~jeh1/2008/TargetCO2_20080407.pdf

[xv] **The 8 Minute Epoch: 65 million Years with James Hansen.** At:
http://www.youtube.com/watch?v=ZGFAWzjO378&NR=1

[xvi] Fig. 1 from Kingsnorth testimony of James Hansen at:
http://www.columbia.edu/~jeh1/mailings/20080910_Kingsnorth.pdf

[xvii] **German Advisory Council on Climate Change Special Report 2006**, Figure 3.1-1. At:
http://www.wbgu.de/wbgu_sn2006_en/wbgu_sn2006_en_voll_3.html

[xviii] W. Kempton et al., **Sea Level Rise and its Effect on Delaware**, Fig. 8. At:
http://co2.cms.udel.edu/SeaLevel_DE.htm

[xix] **Meltwater Pulse 1A**. At: http://en.wikipedia.org/wiki/Meltwater_pulse_1A

[xx] Steven Earle, **Finding the Source of Meltwater Pulse 1A**. Posted inn 2002. At:
http://records.viu.ca/~earles/mwp1a-mar02.htm

[xxi] From http://en.wikipedia.org/wiki/File:Post-Glacial_Sea_Level.png

[xxii] Stefan Rahmstorf, **A new view on sea level rise**, ***Nature Reports Climate Change*** (2010).
At:
http://www.nature.com/climate/2010/1004/full/climate.2010.29.html

[xxiii] Figure from jpl.nasa.gov

[xxiv] From a presentation given by James Hansen to the Club of Rome in 2009. At:
http://www.columbia.edu/~jeh1/2009/ClubOfRome_20091026.pdf

[xxv] Ibid.

[xxvi] GWP Table. At: http://www.climatechangeconnection.org/emissions/CO2_equivalents.htm#GWP

[xxvii] Chad Tolman, **Positive Feedbacks and Climate Runaway – The Need to Act without Delay.** LWV Climate Change Task Force. At: http://www.lwv.org/Content/ContentGroups/StudyTaskforces/GlobalClimateChange/CCTF_BP_PostiveFeedback.pdf

[xxviii] Precautionary Principle. At: http://en.wikipedia.org/wiki/Precautionary_principle

[xxix] In 1978 John H. Mercer wrote an article published in ***Nature*** titled, **West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster.** An abstract is on the web at: http://www.nature.com/nature/journal/v271/n5643/abs/271321a0.html. He wrote, "I contend that a major disaster - a rapid 5 m rise in sea level, caused by deglaciation of West Antarctica - may be imminent or in progress after atmospheric CO_2 content has only doubled. This concentration of CO_2 will be reached within about 50 years if fossil fuel continues to be consumed at its recent accelerating rate."

[xxx] **Cultural Cognition Project Study Examines Why "Scientific Consensus" Fails to Create Public Consensus, Yale Law School, Sept. 13, 2010. At: http://www.law.yale.edu/news/12248.htm**

See also: Naomi Oreskes and Erik M. Conway, **Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoking to Global Warming**, Bloomsbury, 2010.

[xxxi] Naomi Oreskes, **The Scientific Consensus on Climate Change**, ***Science**, **306**, p. 1686.* (2004). At: http://historyweb.ucsd.edu/oreskes/Papers/ScientificConsensusonclimate.pdf

[xxxii] John Cook, **Skeptical Science – Getting skeptical about global warming skepticism**. At: http://www.skepticalscience.com/The-many-lines-of-evidence-for-global-warming-in-a-single-graphic.html